Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-12-01	ADA 392083	

4. Title and Subtitle	5. Report Date
Dynamic Simulation of a Fuel Cell-Powered Electric-Drive Ship	February 2001
	6. Performing Organization Code Project No. 3310.2
7. Author(s) Z. Karni, H. Ghezel, M. Lucas, A. Shecter, G. Rossi	8. Performing Organization Report No. R&DC 441
9. Performing Organization Name and Address John J. McMullen Associates, Inc. 4300 King Street, Suite 400 Alexandria, VA 22302 U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, CT 06340-6096	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTCG39-95-D-E99010 T.O. 98FE00260
12. Sponsoring Organization Name and Address U.S. Department of Transportation United States Coast Guard Operations (G-O) U.S. Coast Guard Headquarters Washington, DC 20593-0001	13. Type of Report & Period Covered Final Report 14. Sponsoring Agency Code Commandant (G-OCU-1) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&D Center's technical point of contact is Robert D. Sedat, 860-441-2684, email: rsedat@rdc.uscg.mil.

16. Abstract (MAXIMUM 200 WORDS)

This report describes a dynamic simulation model (DSM) of an electrically propelled ship with power provided by four 625 kW fuel cells. The model allows prediction of transient responses, and allows design modifications to be made inexpensively prior to hardware construction. Simulations are performed for extreme acceleration and deceleration maneuvers, and the responses are compared to those of diesel and turbine-powered ships. It is concluded that a fuel cell-powered ship can achieve transient responses comparable to those of conventionally powered vessels.

The report documents refinements to the existing DSM model of Fuel Cell Energy (FCE) Corporation's diesel-fueled molten carbonate fuel cell module. The DSM is based on principles of mass and energy balance, and incorporates dynamic characteristics of the fuel cell, all balance-of-plant components, the controller, electric bus, AC propulsion motors, shafting and propellers. Recent changes in FCE's design improve the power module's transient response. Rapid accelerations and crash stop maneuvers were simulated. Results showed the need for careful coordination between available power, the torque absorption of the AC motors, and total system load requirements. For crash stops, shaft brakes were used to reduce propeller RPM. Resistance banks, included in the model, can also be used to absorb excess power, and some fuel cell venting may be required. It is shown that a fuel cell-powered ship can achieve starting and stopping distances considered acceptable under current practice.

17. Key Words	18. Distribution Statement
fuel cell, electric drive, dynamic simulation, ship maneuvering, ship acceleration, head reach parameter	This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	106	

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

EXECUTIVE SUMMARY

Compared to conventional prime movers, fuel cells offer significantly lower emissions, improved fuel economy, lower thermal and noise signatures, and more flexible arrangements. The U.S. Navy and the U.S. Coast Guard are investigating shipboard fuel cell applications including ship service generators and main propulsion using electric drives. Various fuel cell systems have been investigated, and Fuel Cell Energy (FCE) Corporation's molten carbonate fuel cell module powered by standard diesel fuel has been selected for further development. While the steady-state performance of this system is well understood, questions remain about its ability to react to changing load requirements in marine service. It was decided that simulation of dynamic system performance was needed to design systems that could meet these anticipated requirements.

This report describes a dynamic simulation model (DSM) of an electrically propelled ship with power provided by four 625 kW fuel cells. Simulations are performed for extreme acceleration and deceleration maneuvers, and the responses are compared to those of diesel and turbine-powered ships. It is concluded that a fuel cell-powered ship can achieve transient responses comparable to those of conventionally powered vessels.

This report documents refinements to the existing DSM model of FCE's diesel-fueled molten carbonate fuel cell module. The DSM is based on principles of mass and energy balance, and incorporates dynamic characteristics of the fuel cell, all balance-of-plant components, the controller, electric bus, AC propulsion motors, shafting and propellers. Recent changes in FCE's design improve the power module's transient response. Rapid accelerations and crash stop maneuvers were simulated. Results showed the need for careful coordination between available power, the torque absorption of the AC motors, and total system load requirements. For crash stops, shaft brakes and resistance banks were used to absorb excess power, and the need for some fuel cell venting was indicated. It is shown that a fuel cell-powered ship can achieve starting and stopping distances considered acceptable under current practice.

The algorithms for the individual components of the ship powering system were integrated into a SIMSMART™ platform. The SIMSMART™ simulation model includes a ship, electric motors for propulsion, fuel cells, ship controls and auxiliary systems to support the fuel cell. Various variables and parameters can be followed as the model is executed. These variables and parameters include:

1) Propeller RPM, pitch and torque
2) Electric motor current and voltage
3) Flow rates and pressures in the auxiliary support systems
4) Ship speed
5) Fuel cell flow parameters, and
6) System and ship controls.

The main finding of the simulation is that both acceleration and deceleration maneuvers can be performed as rapidly by a fuel cell-powered vessel as by conventional prime movers. Appendices A through E provide detailed explanations of the dynamic simulation of the fuel cell, maneuvering requirements and standards, mathematical formulations developed to run the dynamic simulation, and the user interface to the DSM model. Appendix A contains sections describing the dynamic simulation of the molten carbonate fuel cell (MCFC). This material was primarily provided by Fuel Cell Energy (FCE) based on work done at the University of Pennsylvania under a subcontract to FCE. These sections contain the description of the building components of the MCFC. Mathematical descriptions of these components were used to develop the time stepping, dynamic simulation. The criteria used to evaluate responsiveness of the propulsion system are based on a survey of maneuvering requirements and standards. This report is included as Appendix B to this report. Appendix C contains the detailed description of the response curve generation and mathematical formulations used in the dynamic simulation. The detailed description of the building components of a marine propulsion system in mathematical formulation is described in Appendix D. This integrated ship and fuel cell propulsion system dynamic simulation was produced by John J. McMullen Association (JJMA) using Matlab™ and Simulink™ algorithms. In addition to the MCFC, the modeled ship power system components include the propeller, the AC motor and the complex control system to govern the required changes in ship's speed at maneuvering. Icons and computer monitor displays used in the dynamic simulation are presented in Appendix E. These are the user interfaces to the DSM.

The simulation tool developed is sufficiently generic and can be used to optimize the control scheme for maneuvering for any other vessel with an integrated electric power system. Further ship maneuvering simulations are needed to determine optimum system configuration and control settings for using fuel cells for ship propulsion. Maneuvering performance of a fuel cell-powered ship is expected to be acceptable. The current simulation model will be used in future work to assess the system's ability to meet ship service requirements.